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Port Hueneme, California 93043-4370

Contract Report
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**CORRELATION OF
SURFACE CHLORIDE CONCENTRATION OF
A PILE EXPOSED TO THE MARINE
ENVIRONMENT TO THE ADHESIVENESS OF
A COMMERCIALY AVAILABLE EPOXY**

An Investigation Conducted By

J. A. Beran, Ph.D.
Department of Chemistry
Texas A&M University
Kingsville, TX 78363

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EXECUTIVE SUMMARY

The U.S. Navy is studying the use of carbon fiber reinforced plastic (CFRP) for retrofitting the strengths of piers and piles. The CFRP is adhered to the piers and piles with a commercial adhesive. Several of those investigations have been (and are being) conducted at the Navy Facilities Engineering Service Center (NFESC) at Port Hueneme, California. One area of investigation relates to the effectiveness of the epoxies under different environmental exposures of the concrete. Most other investigations have been conducted with "virgin" concrete samples of pier and pile.

A pile that has been exposed to marine conditions for approximately 4 years was removed from the harbor at Port Hueneme. The pile was transferred to the NFESC service yard at which point several parameters for the adhesiveness of an epoxy to the concrete pile surface were investigated.

The effect of chloride levels, with and without hydroblasting surface preparation, on the adhesiveness of an epoxy applied to the surface of the pile, with and without the application of primer, was investigated. The laboratory analysis of chloride levels on the surface of the concrete pile and the pull-off forces of the adhesive were the principal parameters upon which the research was focused.

In general it was found that adhesion would somewhat decrease with chloride content. The use of hydroblasting and pretreatment with a primer increased the adhesion in all cases, and both are recommended.

Keywords: chloride, epoxy, carbon fibers, piles, reinforced concrete

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1. INTRODUCTION

This investigation covers the effect of chloride concentrations at the surface of two piles on the adhesiveness of two epoxies (Sikadur 30 and 32) commonly used for adhering carbon fiber reinforced plastic to concrete. The fifteen-foot concrete piles had been exposed to the marine environment at Port Hueneme, CA for approximately 4 years (Figure 1). The vertical position in the harbor permitted the piles to be exposed to the atmosphere above the average high tide level to below the average low tide level in the water. They were removed from the harbor and relocated to the service yard of the NFESC.



Figure 1. Piles in the harbor

Several parameters were studied to determine the adhesiveness of the epoxy as a function of the changes in chloride concentrations from top to bottom, mostly along pile #1. The chloride and adhesion tests were conducted at approximately one-foot intervals from top (identified as the pile end that was out of the water) to bottom, along the pile. The pile extended from about 7 3/4 feet *above* the average high tide level to about 1 foot *below* the average low tide level for May 1998 (Figure 2).

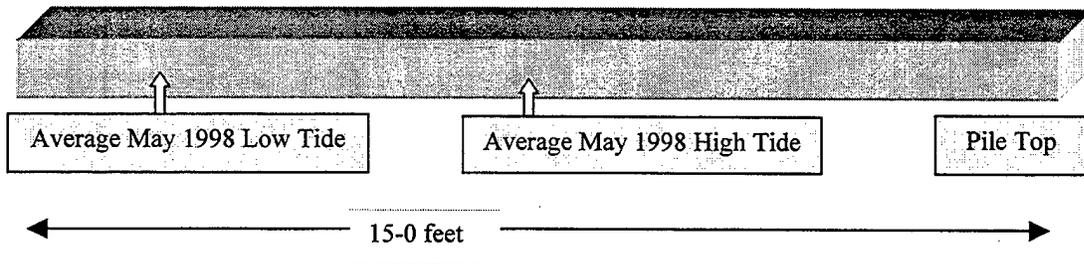


Figure 2. Pile Schematic.

2. PILE PREPARATION

Two vertically positioned piles located in the Port Hueneme harbor were removed and transferred to the NFESC service area. The piles were distinguished by numbers #1 and #2

with faces identified as A, B, C, and D. Face A of both piles is the top-side-up face of the concrete forms, faces B, C, and D are all form faces (sides and bottom, smoother and less pitted). The crustacean material from Pile #1, Faces A and B and Pile #2, Faces A and D were removed by hand scrapping. The faces were then hydroblasted with a power sprayer at 200 psi. All data of this report were obtained from Pile #1.

From the tidal chart of May, 1998, the average high tide line was about 7 ¾ feet from the “top” of the pile and the average low tide line was about 13 ft from the “top” of the pile.

The pile was marked at approximately one-foot intervals, starting at the ½ foot mark at the top of the pile.

2.1 Application of Test Dollies

Carbon fiber reinforced plastic (CFRP) circles were formed to the size of the aluminum dollies. CFRP circles and dollies were then adhered to Pile #1 (Figure 3).

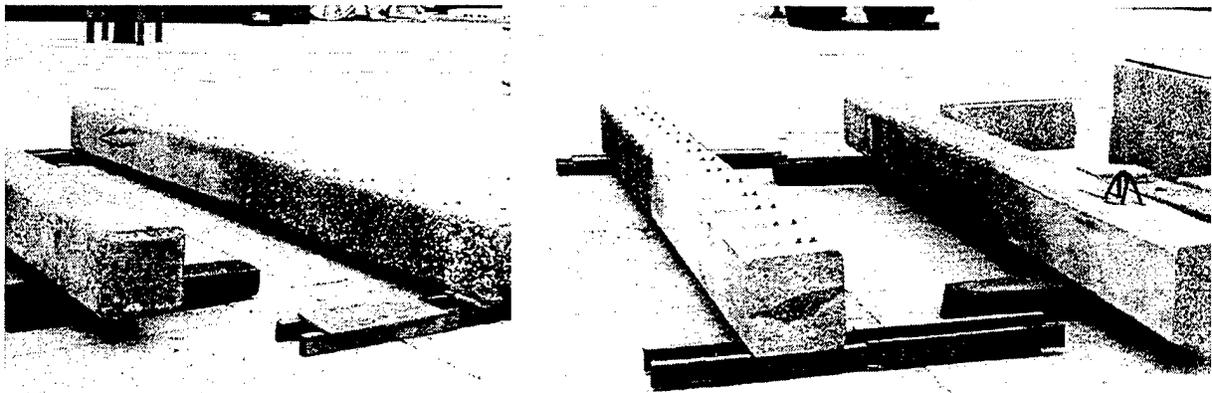


Figure 3. Piles at NFESC showing adhered dollies.

Sikadur 32 epoxy was used to adhere two aluminum dollies with CFRP circles at *each* of the marked positions of Pile #1, Face A. Sikadur 30 epoxy was used to adhere two aluminum dollies with CFRP circles at *each* of the marked positions of Pile #1, Face B. Finally, Sikadur 30 was also used to adhere two aluminum dollies with CFRP circles at *alternate* (with an additional application at the 7 ½ foot position) marked positions of Pile #1, Face D. Temperature and relative humidity conditions were recorded.

2.2 Procedure for Testing the Adhesiveness of Epoxy

The epoxy (adhered to the dolly and the CFRP circle) was allowed to cure for at least seven (7) days.

A 500 psi elcometer (Figure 4) was used to remove the dollies and the force (or tensile stress) required was recorded. Since two dollies were available at each marked position along the pile, the average of the two tensile strength values was used for a subsequent analysis of the data. The diameter of a dolly was 0.787 inch (20 mm) and its area was 0.487 square inch.



Figure 4. Elcometer

3. CHLORIDE ANALYSIS

3.1 Concrete Sample Extraction

An impact drill was used to extract surface samples from Pile #1, Faces B and D at the marked positions, collecting about 20 grams of concrete sample at each location. Samples were less than one-quarter inch in depth, as shown at right in Figure 5 photos.

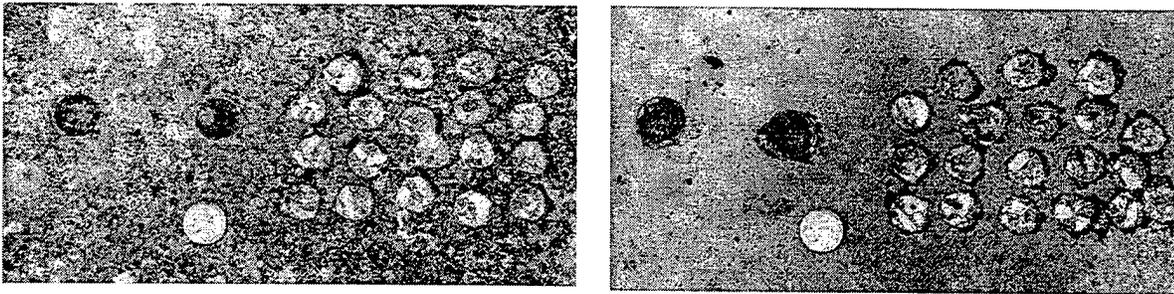


Figure 5. Pile #1, Faces B and D.

Approximately 10 grams of the very finely divided (powdered) part of the sample was subsequently used for the chloride analysis.

3.2 Chloride Measurement

The chloride analyses were performed using a chloride ion selective electrode. The meter used for the analysis was standardized using standardized solutions of chloride ion, 10 PPM, 100 PPM and 1000 PPM. All checks/tests indicated that the meter was performing

according to the manufacturer's calibration procedures; additionally, excellent linearity with the standardized solutions was obtained.

3.3 Experimental Procedure for Preparing Concrete Samples

The experimental procedure for preparing the concrete samples from the marked positions of the pile for chloride analysis was (in brief) [1]:

- A quantitative mass (about 10 grams) of very finely divided concrete sample was measured.
- Sample was mixed with 50.0 mL of deionized (DI) water, heated to boiling for 5 minutes (covered), and allowed to set for 24 hours.
- The sample solution was filtered; the concrete sample was washed with 50.0 mL of DI water, acidified with 1:1 nitric acid, and momentarily heated to boiling.
- The sample solution was cooled to ambient temperature, adjusted to an approximate pH of 5 with a potassium hydroxide solution, and diluted to volume with DI water in a 100 mL volumetric flask.
- A 2 mL aliquot of ion strength adjuster (ISA) solution was pipetted into the 100 mL volumetric flask before the chloride concentration was determined.

3.4 Experimental Procedure for Chloride Analysis of Concrete Samples

The measurement of the chloride concentrations of the surface samples at the marked positions on the pile was as follows (Figure 6) [1]:

- The chloride meter was calibrated with standard solutions of 10 ppm (parts per million by mass), 100 ppm, and 1000 ppm chloride concentrations before and after each set of analyses. A standardization curve of the data (millivolt vs. ppm chloride) was constructed.
- Millivolt readings for each sample solution were determined (10 minutes were allowed for each measurement to reach stability). The standardization curve was used to determine the chloride concentrations (at the ppm levels) in the sample solution.
- Calculations: from the known volume of the sample solution, the mass of chloride in the sample solution was calculated. From the measured mass of the original sample, the ppm chloride of the surface sample at each of the marked positions along the pile was calculated.



Figure 6. Chloride analysis setup

4. ADHESIVE FORCES ON SURFACE OF PILE #1

4.1 Adhesion of Sikadur 30 Epoxy on Hydroblasted Surface.

Figure 7 shows the actual pull-off forces of the dollies placed at 1 foot intervals along Pile #1, Face B. The “connected” data points represents the average pull-off force at each sample site.

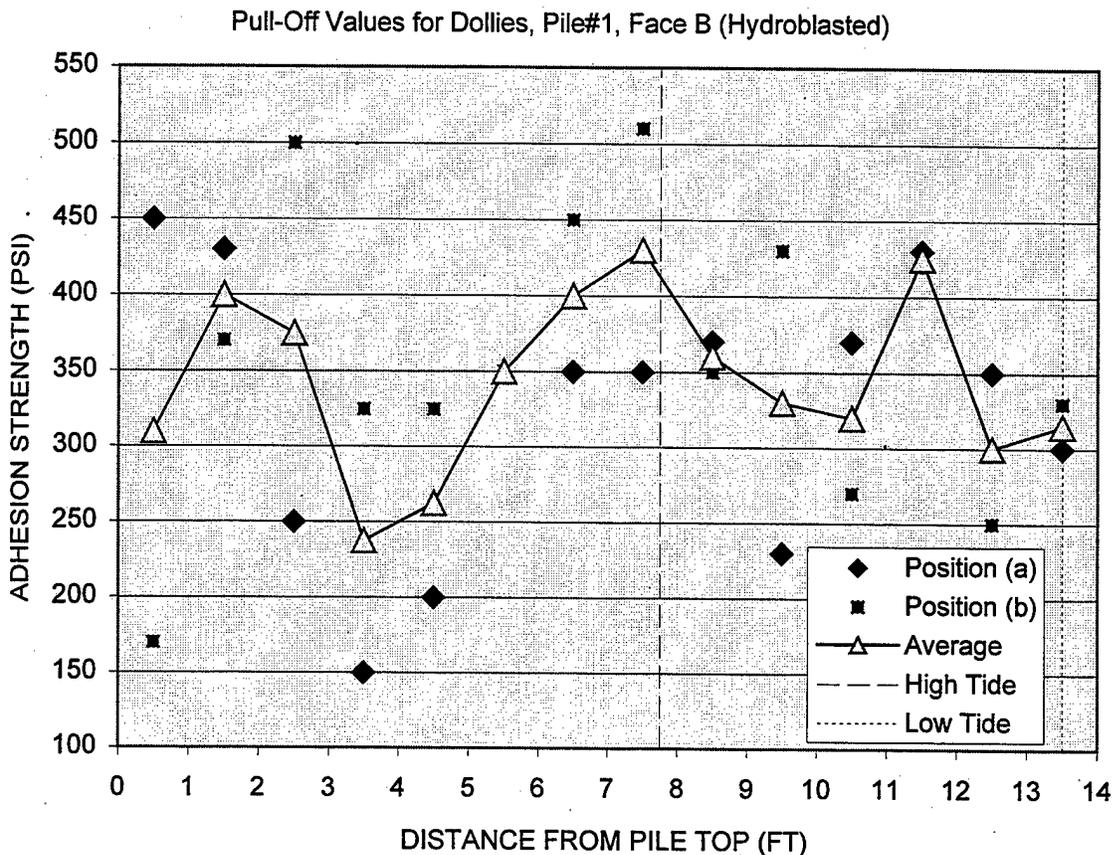


Figure 7. Pull-off stress required to remove the adhered dollies along the pile with a hydroblasted surface

The average “tidal zone” for the month of May, 1998 was from about 7 ¾ ft to 13 ½ ft along the pile. From the data of Figure 7, there appears to be a somewhat higher adhesiveness just above the average high tide level (at 7 ½ feet from the pile top), and then again at a much larger distance from the high tide level (at 18 inches from the pile top). The latter positioning could be consider a region that lies above the “splash zone” of the water. Within the tidal zone and lower, there seems to be little variation in adhesiveness of the epoxy.

4.2 Adhesion of Sikadur 30 Epoxy on Nonhydroblasted Surface

Figure 8 shows the actual pull-off forces of the dollies placed at 1 foot intervals along Pile #1, Face D. The “triangular” data points represent the average pull-off force at each sample site.

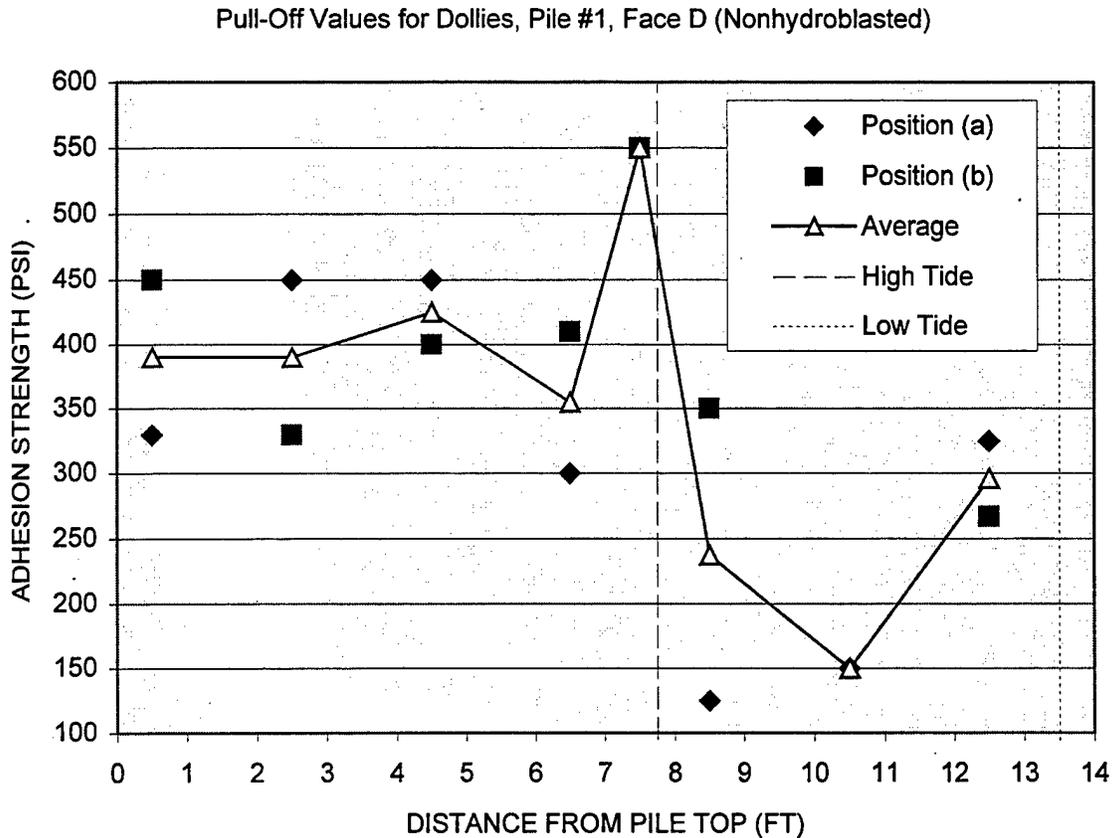


Figure 8. Pull-off stress required to remove the adhered dollies along the pile with a non-hydroblasted surface

With fewer data points than on the hydroblasted surface (Figure 7), the adhesiveness of the epoxy on a non-hydroblasted surface (Figure 8) seems to somewhat correlate with the data of the hydroblasted surface, with a higher adhesiveness just above the average high tide level (at 7½ feet from the pile top).

4.3 Adhesion of Sikadur 30 Epoxy on Hydroblasted and Nonhydroblasted Surface

Figure 9 compares the pull-off forces for the dollies adhered to a hydroblasted surface (Face B) with those of a nonhydroblasted surface (Face D), using the Sikadur 30 epoxy.

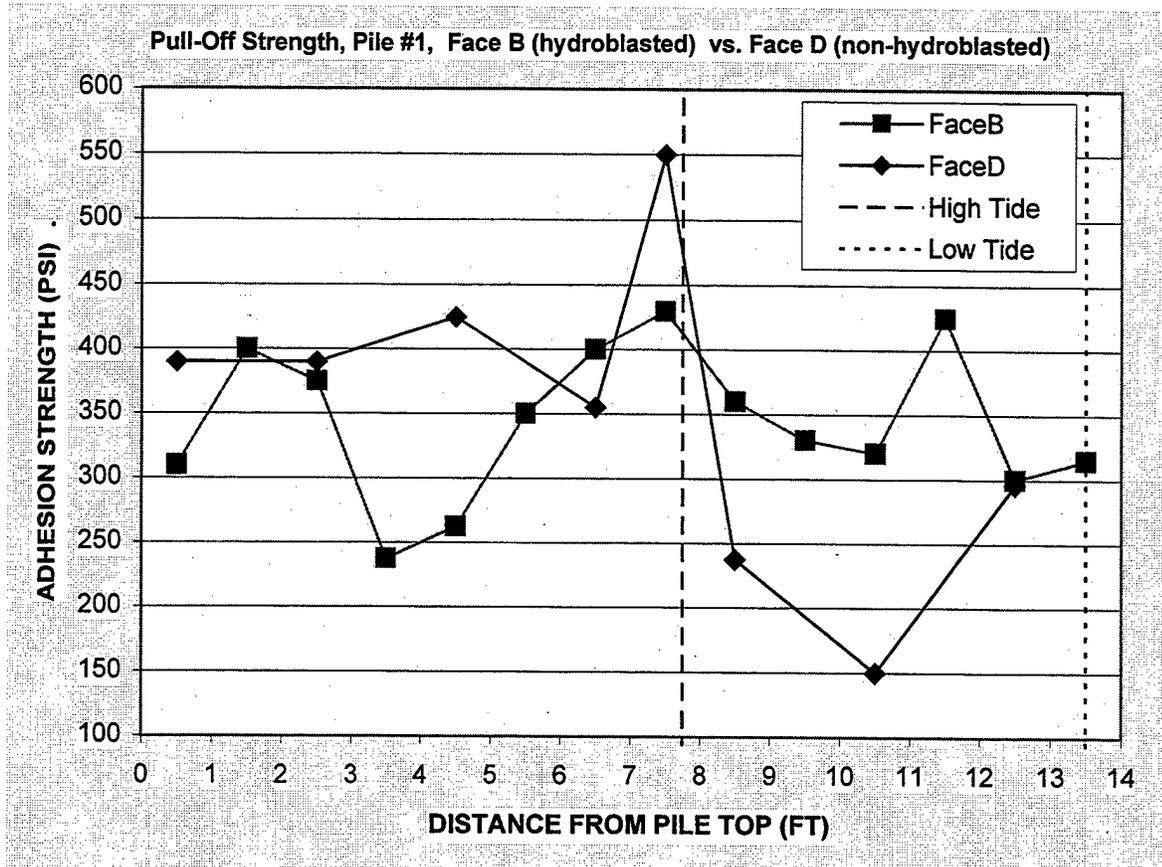


Figure 9. Comparison of the Adhesiveness of Sikadur 30 Epoxy on a Hydroblasted Surface (Face B) and a Nonhydroblasted Surface (Face D)

Figure 9 summarizes the data of Figures 7 and 8. The correlation of the adhesiveness of Sikadur 30 between the two surfaces with different preparations, while not quantitative, does appear to exist. It also appears that hydroblasting resulted in minimum adhesion values around 240 psi, in excess of the minimum 150 psi for nonhydroblasting. The improvement is more obvious in the intertidal zone.

4.4 Adhesion of Sikadur 30 Epoxy on Hydroblasted Surface with a Pretreatment of Sikadur 55 Primer

Figure 10 shows the actual and average pull-off forces of the dollies placed at 1-foot intervals along Pile #1, Face B in which the surface had not only been hydroblasted but also pretreated with Sikadur 55 primer. The “connected” triangular data points represent the average of the two dollies at that location along the pile surface.

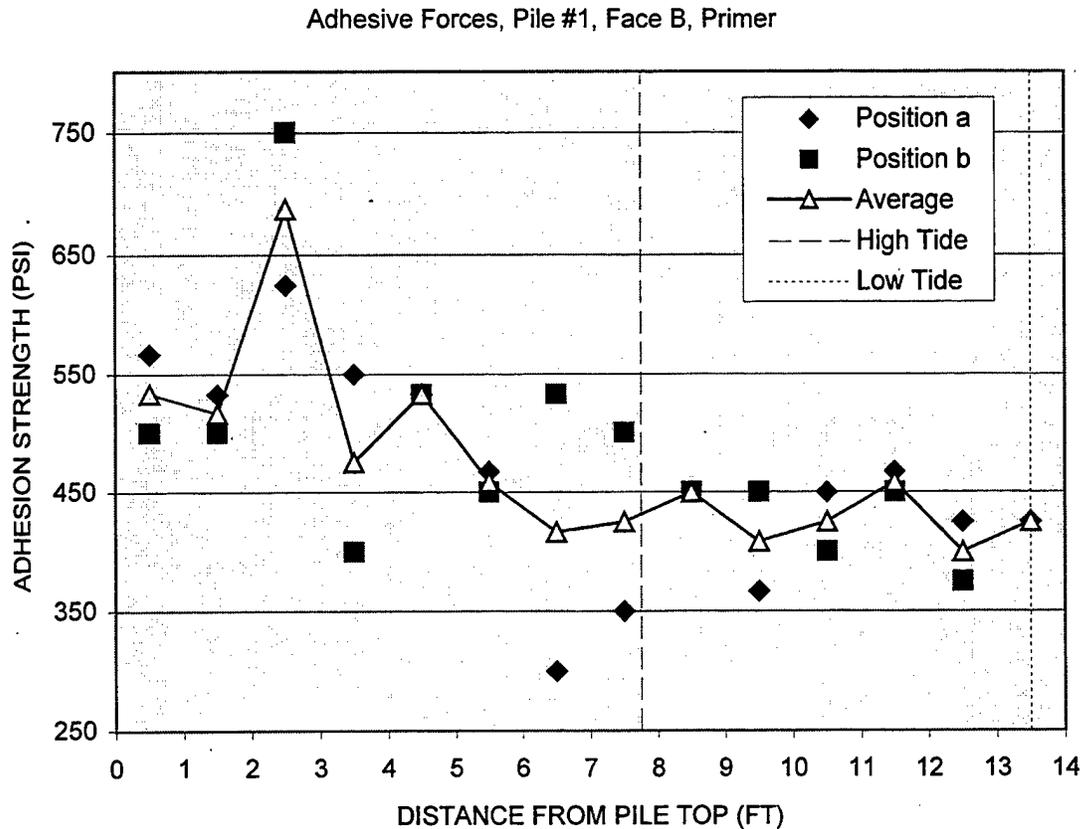


Figure 10. Adhesion strength with Sikadur 30 and Sikadur 55 Primer, Pile #1, Face B.

The plotted data of Figure 10 indicates a greater adhesiveness of the Sikadur 30 epoxy above the tidal zone than below the tidal zone. This trend was not as apparent on the surfaces in which the Sikadur 55 primer was not used (both Faces B and D, Figure 9). The data appears to indicate that the application of Sikadur 55 results in a higher adhesiveness above the high tide level.

4.5 Adhesion of Sikadur 30 Epoxy on a Hydroblasted Surface, With and Without the Application of Sikadur 55 Primer

Figure 11 is the plotted data of the adhesiveness of Sikadur 30 with and without the application of Sikadur 55 primer to Pile #1, Face B (hydroblasted).

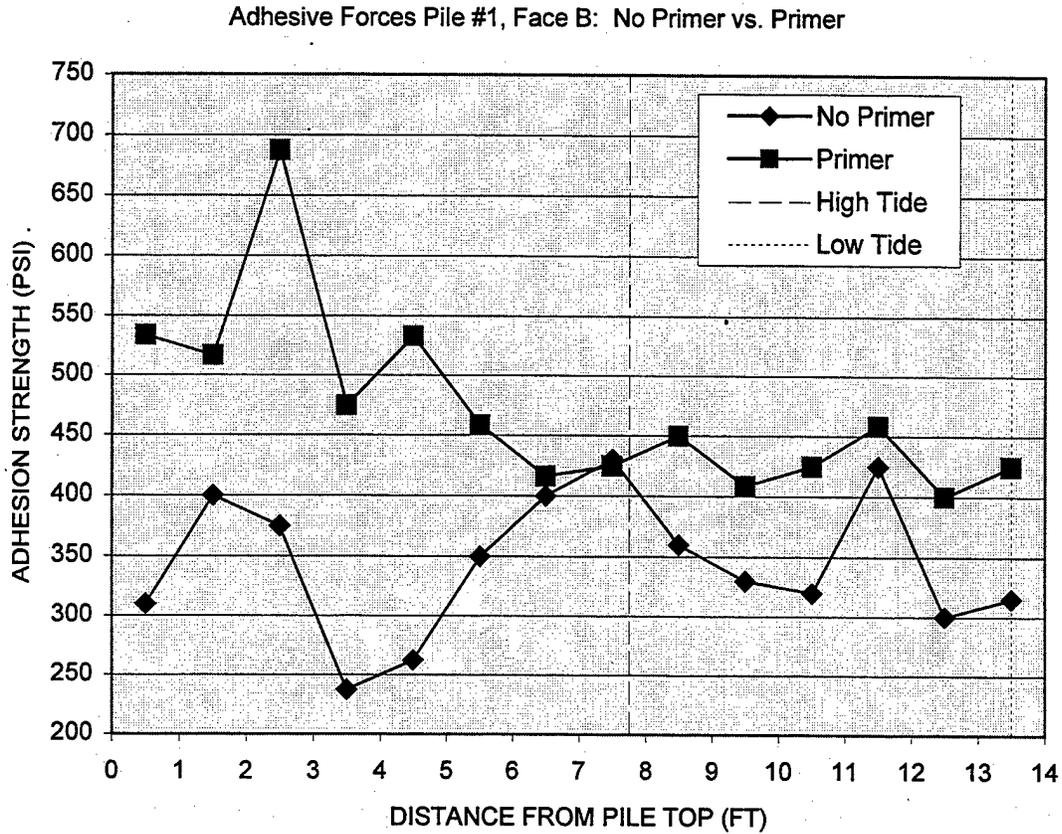


Figure 11. A Comparison of the Adhesiveness of Sikadur 30 With and Without the Application of Sikadur 55 Primer

The plotted data of Figure 11 indicates that along the entire length of the pile, the application of Sikadur 55 primer enhances the adhesiveness of the Sikadur 30 epoxy. The differentiation is most apparent above the high tide line (above the tidal zone).

4.6 Adhesion of Sikadur 32 Epoxy on Hydroblasted/Non-Form Surface

Figure 12 shows the actual pull-off forces of the dollies placed at 1 foot intervals along Pile #1, Face A. The “triangular” data points (connected) represent the average pull-off force at each sample site.

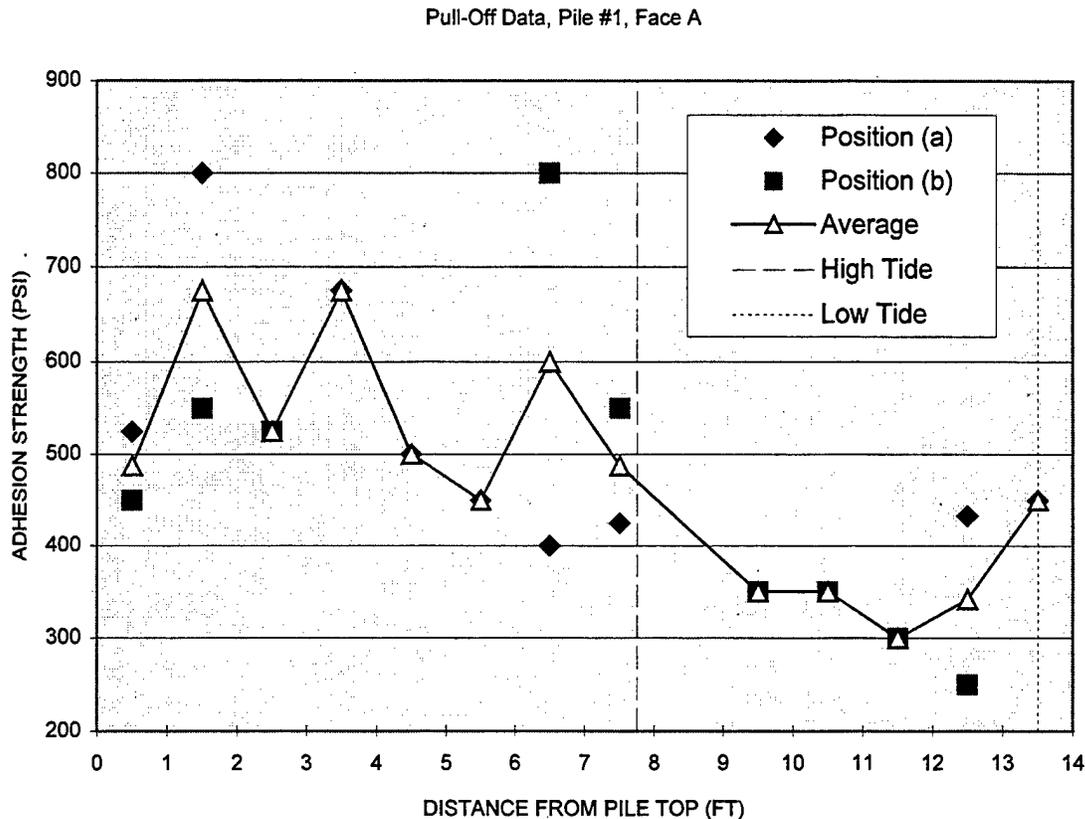


Figure 12. Pull-Off Forces Required to Remove the Adhered Dollies Along the Pile with a Hydroblasted Surface

Figure 12 shows a similar trend to that of Figure 9. While the epoxies are not the same (Sikadur 32 vs. Sikadur 30 respectively), the adhesiveness appears to be greater for the concrete that is generally out of the water (average high tide line is 7 ¾ ft) than the region generally in the water.

5 CHLORIDE CONCENTRATIONS ON THE PILE SURFACE

5.1 Surface Chloride Concentrations on Hydroblasted Surface

Figure 13 shows the chloride concentrations of the surface samples of Pile #1, Face B. Alternate sample analyses at the marked sample sites on the pile were conducted on separate days.

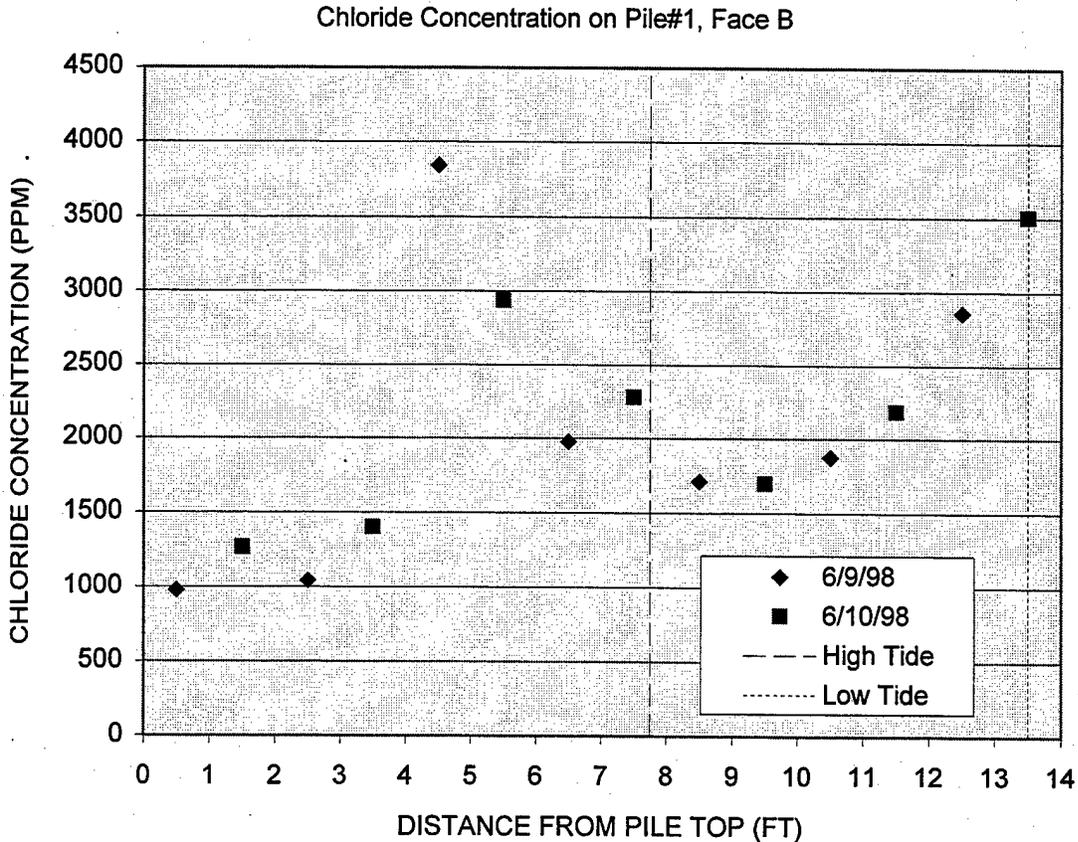


Figure 13. Chloride Concentrations at the Surface of a Hydroblasted Face

The average “tidal zone” for the month of May, 1998 was from about 7 $\frac{3}{4}$ ft to 13 $\frac{1}{2}$ ft along the pile. The data reflect what might be expected: above the average high tide (what might be considered the splash zone along the pile, a region that is not continually washed by tidal action) the chloride levels are comparatively high and decreasing with distance away from the high tide level; within the tidal zone (where a continuous washing of the pile surface occurs) there is a lesser variation in the surface chloride concentrations; and near or below the average low tide (where chloride levels remain constant to the water), the chloride levels increase slightly.

5.2 Surface Chloride Concentrations on Nonhydroblasted Surface

Figure 14 show the chloride concentrations of the surface samples on Pile #1, Face D.

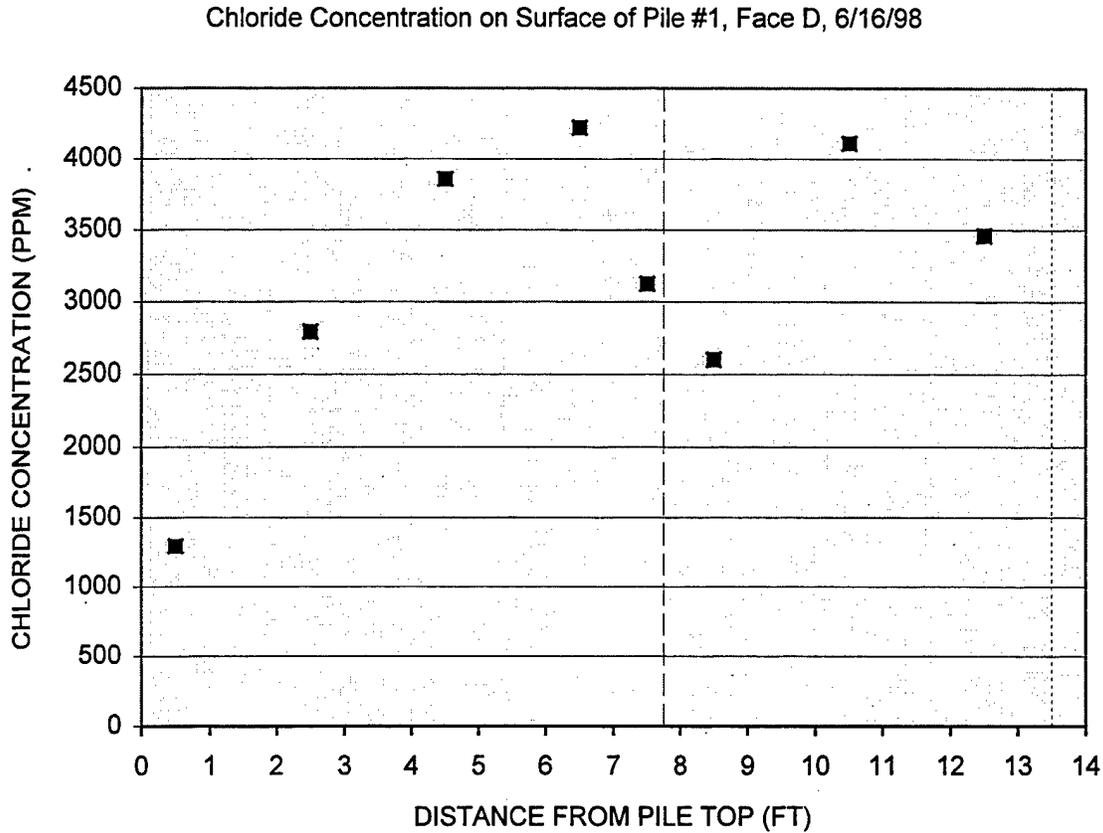


Figure 14. Chloride Concentrations at the Surface of a Nonhydroblasted Face

The average "tidal zone" for the month of May, 1998 was from about 7 ¾ ft to 13 ½ ft along the pile. Again, with fewer data points in Figure 14 than Figure 13, the same correlation of surface chloride concentrations above, in, and below the tidal zone appears. Figure 15, below, summarizes the two sets of data.

5.3 Surface Chloride Concentrations on Hydroblasted and Nonhydroblasted Face

Figure 15 compares the surface chloride concentrations of a hydroblasted surface (Face B) and a nonhydroblasted surface (Face D).

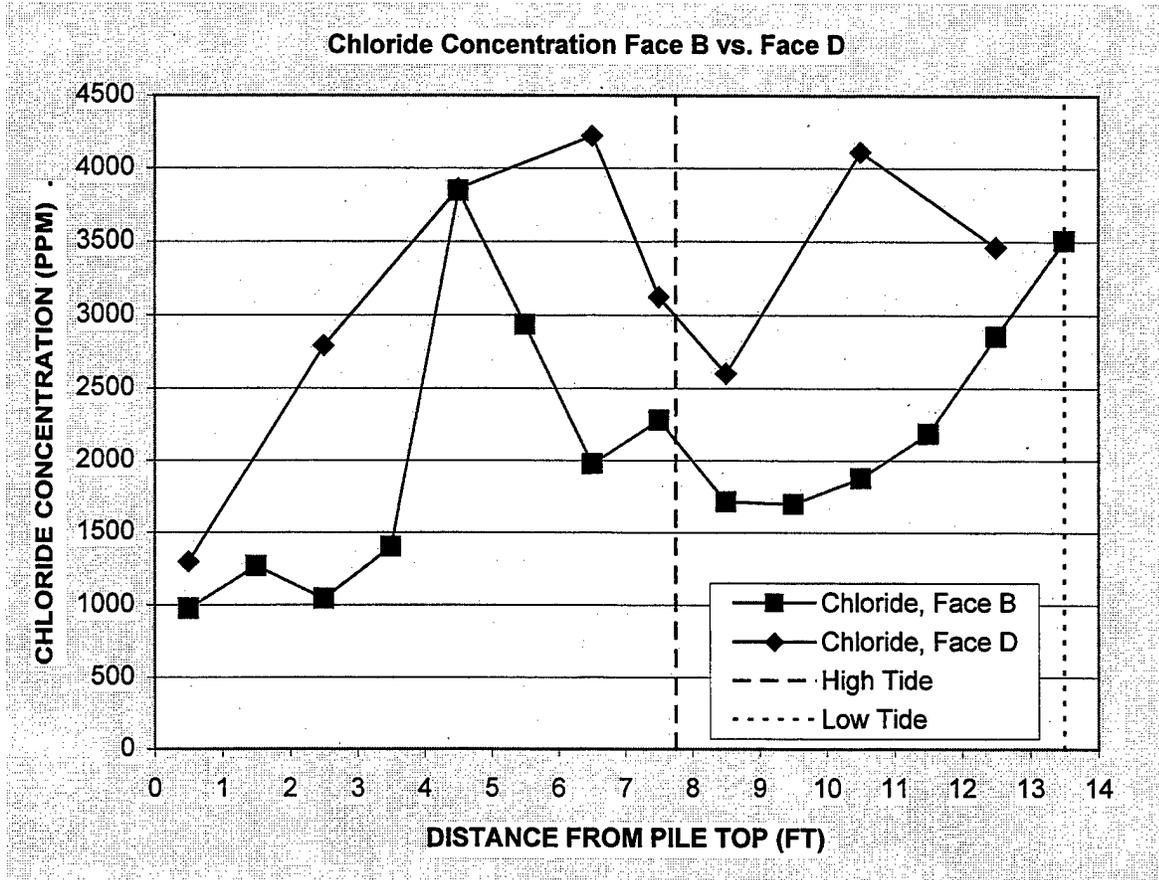


Figure 15. A Comparison of the Surface Chloride Concentrations of a Hydroblasted Surface (Face B) and the Surface Chloride Concentrations of a Nonhydroblasted Surface (Face D)

Figure 15 is a summary of Figures 13 and 14. The chloride levels are slightly higher on the nonhydroblasted surface (which may be expected); the surface chloride levels are higher just above the tidal zone, and near/below the low tide line.

As the distance increases from the high tide line toward the top of the pile, the chloride levels decrease. This trend is expected because of the lower concentration of the salt water spray from the tidal action of the harbor environment.

6. THE ROLE OF CHLORIDE ON THE ADHESIVENESS OF SIKADUR 30 EPOXY

6.1 The Correlation of Surface Chloride Concentrations of a Hydroblasted Surface to the Adhesiveness of the Sikadur 30 Epoxy

Figure 16 shows how the chloride concentrations along the surface of Pile#1, Face B (a hydroblasted surface) relates to the adhesiveness of the Sikadur 30 epoxy.

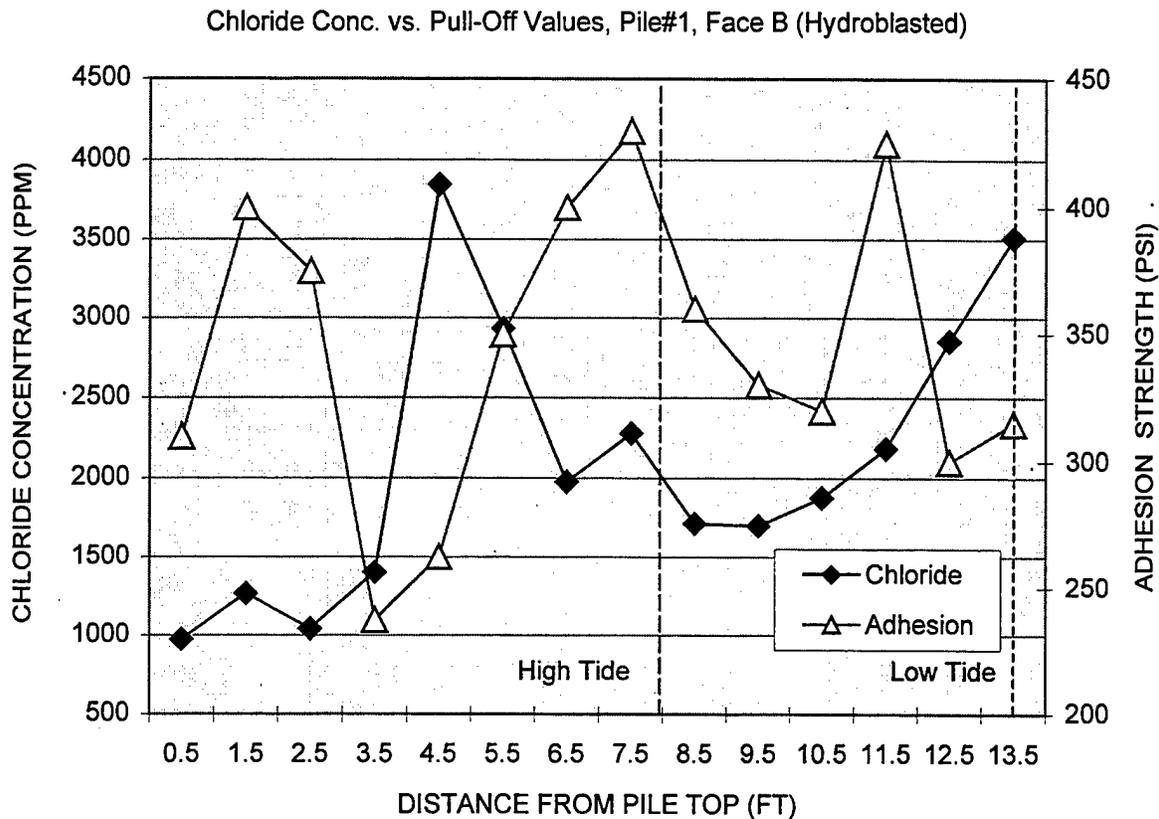


Figure 16. Chloride Concentrations along Pile #1, Face B (hydroblasted) vs. Adhesiveness of the Sikadur 30 Epoxy

Figure 16 appears to produce little indication of a correlation between increasing surface chloride concentrations to the adhesiveness of the Sikadur 30 epoxy. Figure 17 appears to have more meaning.

6.2 The Inverse Correlation of Surface Chloride Concentrations of a Hydroblasted Surface to the Adhesiveness of the Sikadur 30 Epoxy

Figure 17 shows how the chloride concentrations along the surface of Pile#1, Face B (a hydroblasted surface) relates to the *inverse* of the adhesiveness of the Sikadur 30 epoxy.

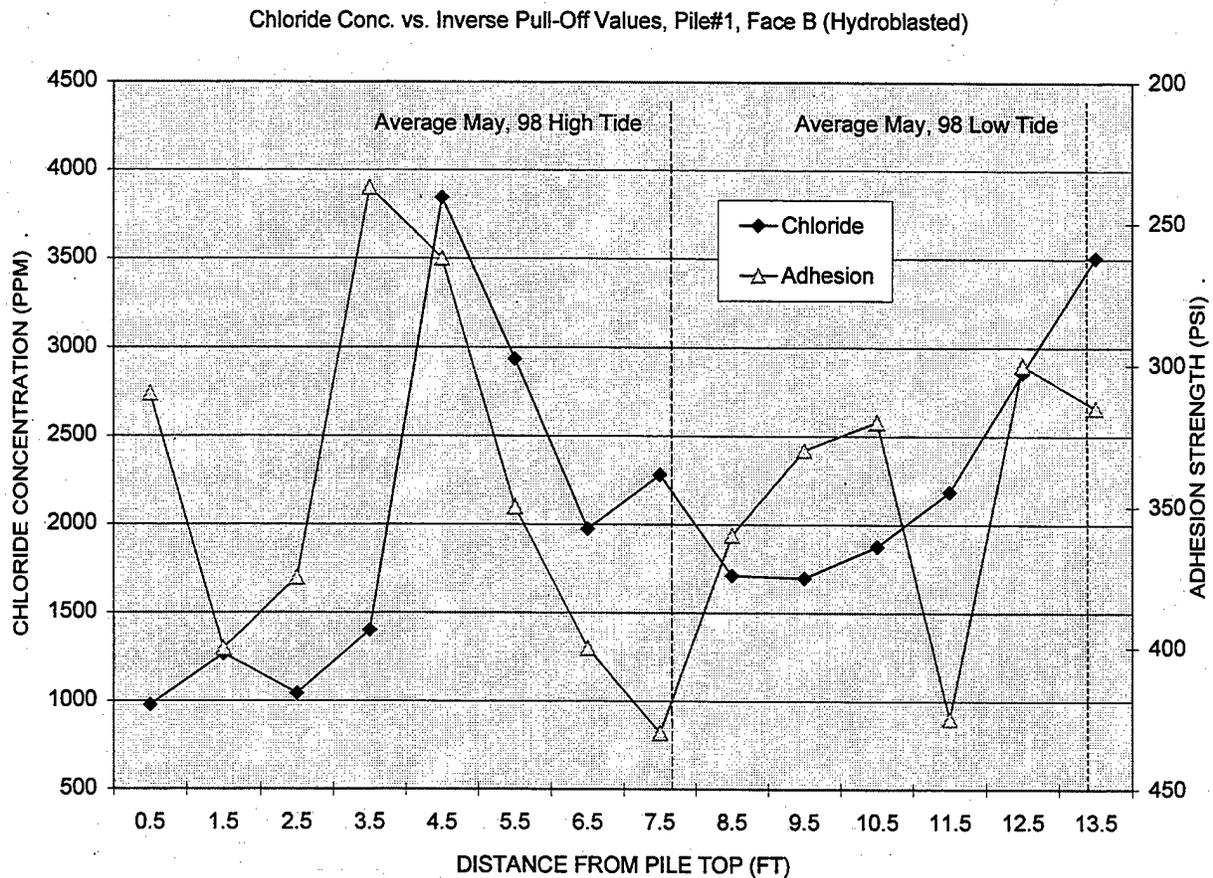


Figure 17. Chloride Concentrations along Pile #1, Face B (a hydroblasted surface) vs. the Inverse Adhesiveness of the Epoxy

Figure 17 is an inverse correlation of chloride levels and adhesiveness. The plotted data shows that high surface chloride concentrations results in a decreased adhesiveness in the Sikadur 30 epoxy. The correlation is mostly apparent in the region of the pile above the average high tide, the region of the pile generally consider out of the water.

At the top of the pile, where the surface chloride levels are lower, the adhesiveness generally increases again.

6.3 Correlation of Surface Chloride Concentrations of a Hydroblasted Face to the Adhesiveness of the Sikadur 30 Epoxy With Sikadur 55 Primer

Figure 18 shows the plotted data of the surface chloride concentrations and the adhesiveness of Sikadur 30 with the application of Sikadur 55 primer.

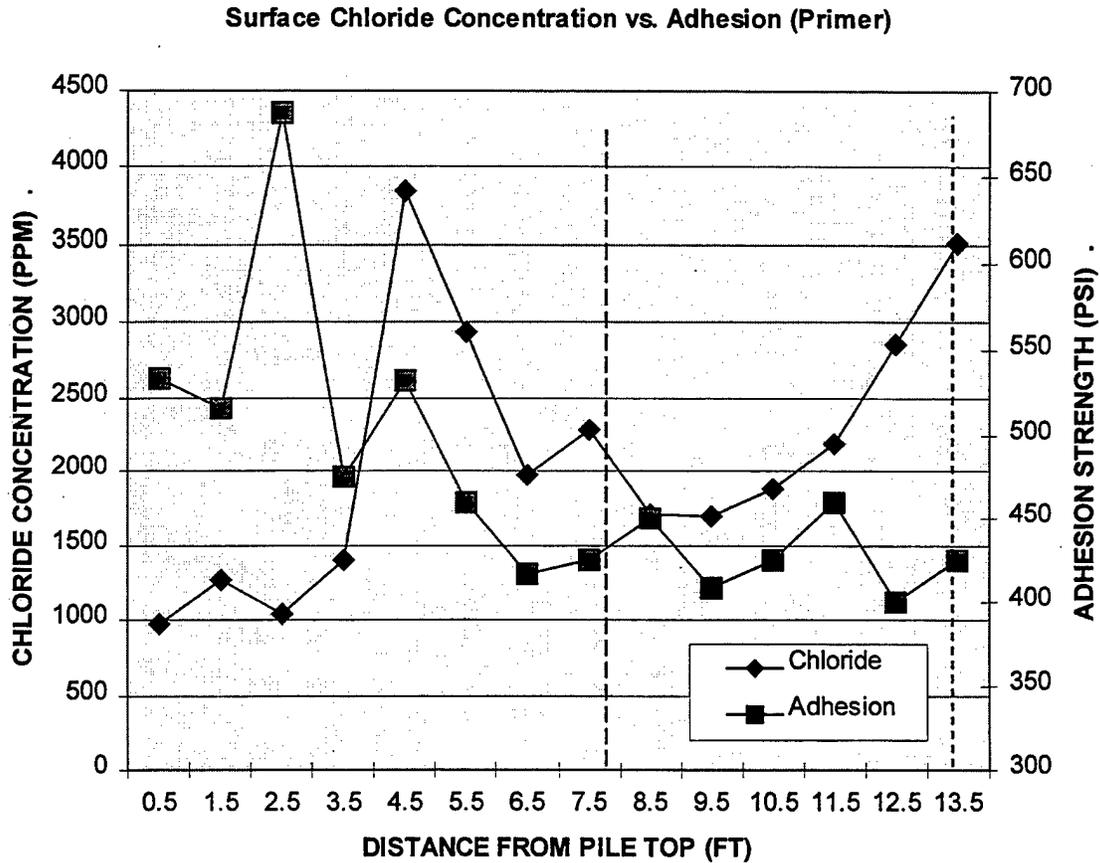


Figure 18. A Correlation of the Surface Chloride Concentrations and the Adhesiveness of Sikadur 30 With the Application of Sikadur 55 Primer Along Pile #1, Face B.

The plotted data of Figure 18 does not indicate much of a correlation between the chloride levels and the adhesiveness of the Sikadur 30 epoxy. It may be hypothesized that primer has a more significant effect on the adhesiveness of the Sikadur 30 epoxy than does the surface chloride concentrations. Additionally the concrete above the tidal zone may be more dense/compact (higher compressive strength) than within or below the tidal zone. See Figures 27 and 28.

6.4 The *Inverse* Correlation of Surface Chloride Concentrations of a Hydroblasted Surface to the Adhesiveness of the Sikadur 30 Epoxy With the Application of Sekadur 55 Primer

Figure 19 shows the effect of the surface chloride concentrations on the adhesiveness of the Sikadur 30 epoxy with the pre-application of Sikadur 55 primer.

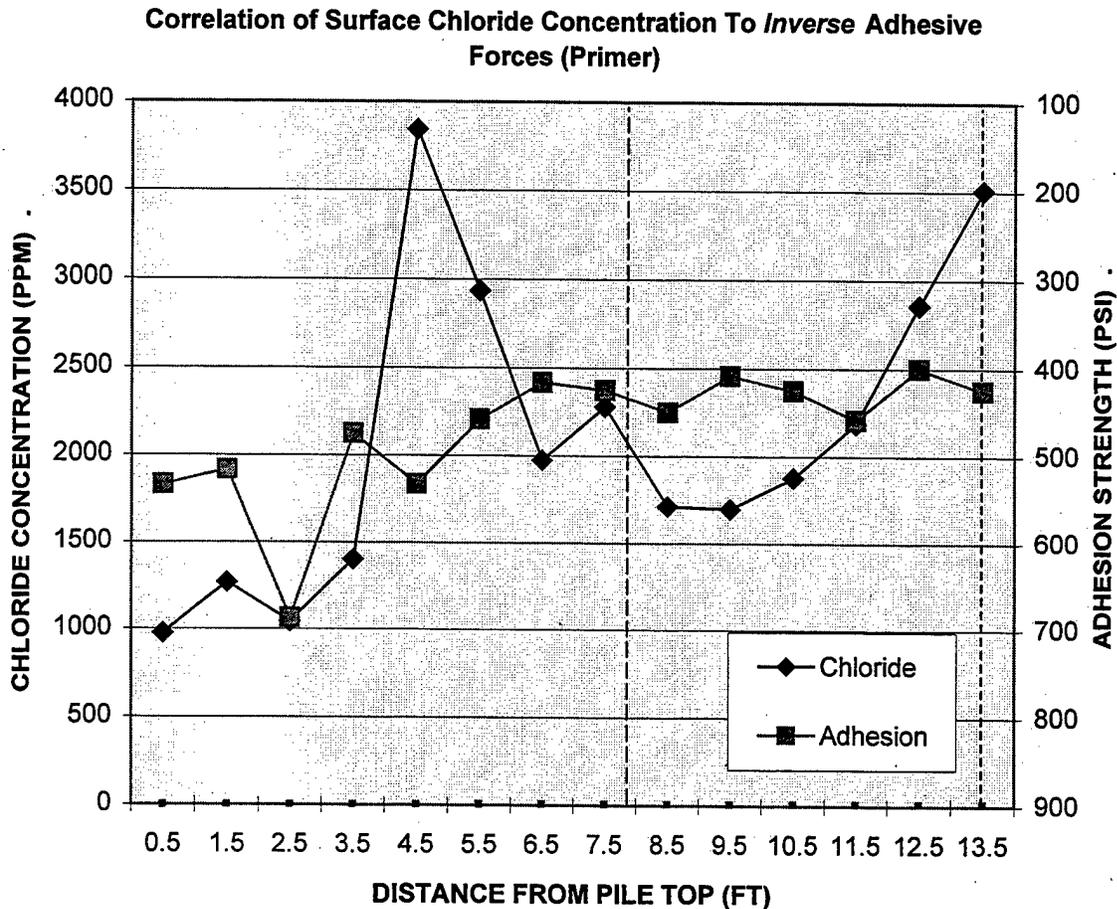


Figure 19. Inverse Correlation of the Surface Chloride Concentrations and the Adhesiveness of Sikadur 30 With the Application of Sikadur 55 Primer, Pile #1, Face B.

The plotted data of Figure 19 does not show the strong inverse correlation that was observed for the data in which the Sikadur 55 primer was not used (see Figures 17 and 23). Again, the presence of the Sikadur 55 primer may override some of the effects of the surface chloride concentrations. However, at the top of the pile, the highest adhesion values are indeed obtained for the lowest chloride concentrations.

6.5 The Correlation of Surface Chloride Concentration to Adhesiveness of Sikadur 30 With and Without the Application of Sikadur 55 Primer

Figure 20 summarizes the effect of surface chloride concentrations of the adhesiveness of Sikadur 30 with and without the application of Sikadur 55 primer on Pile #1, Face B (hydroblasted).

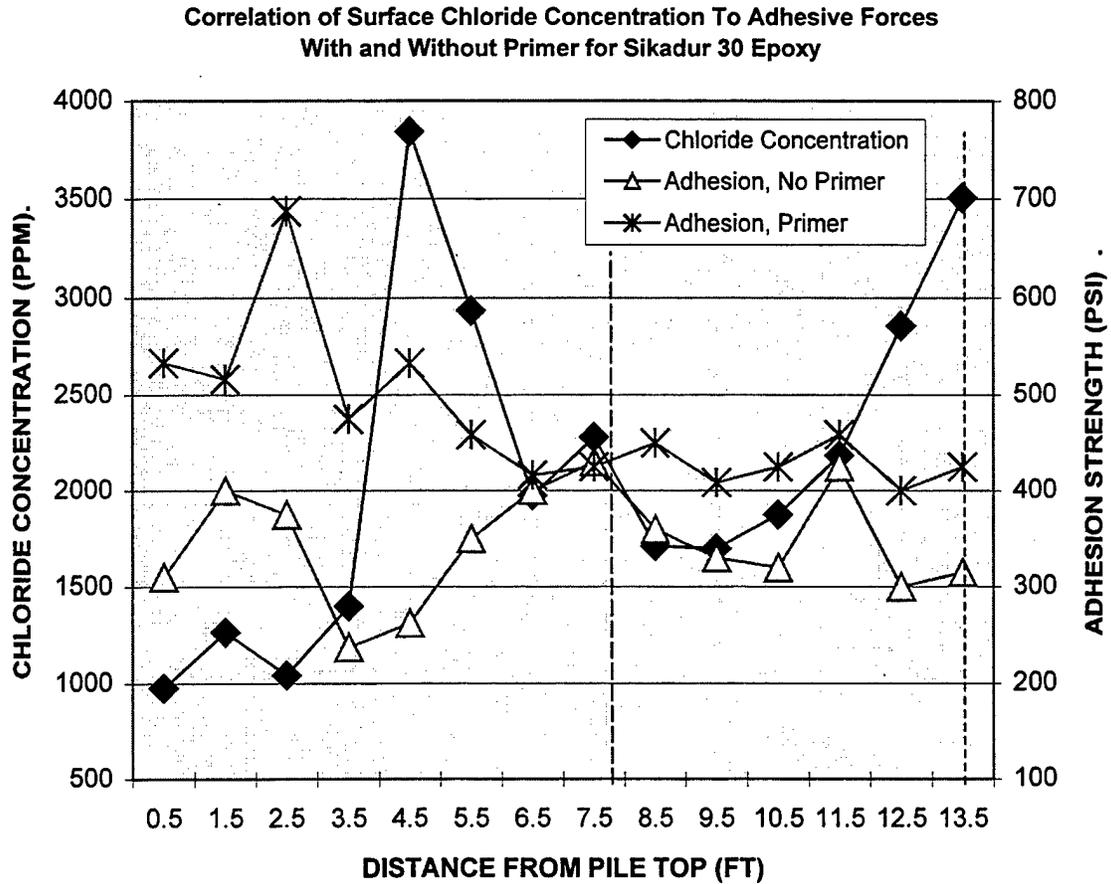


Figure 20. Summary of Surface Chloride Concentrations and Adhesiveness of Sikadur 30 Epoxy to Pile #1, Face B, With and Without Sikadur 55 Primer

The plotted data of Figure 20 summarizes the data of Figures 16 and 18. The surface chloride concentrations would seem to inversely correlate with the adhesiveness of the Sikadur 30 epoxy with the Sikadur 55 primer, but not so without the primer.

6.6 The *Inverse* Correlation of Surface Chloride Concentration to Adhesiveness of Sikadur 30 With and Without the Application of Sikadur Primer

Figure 21 assumes the same correlation that appeared in Figure 20, except of the inverse correlation. A strong evidence of the inverse correlation was apparent in earlier plotted data.

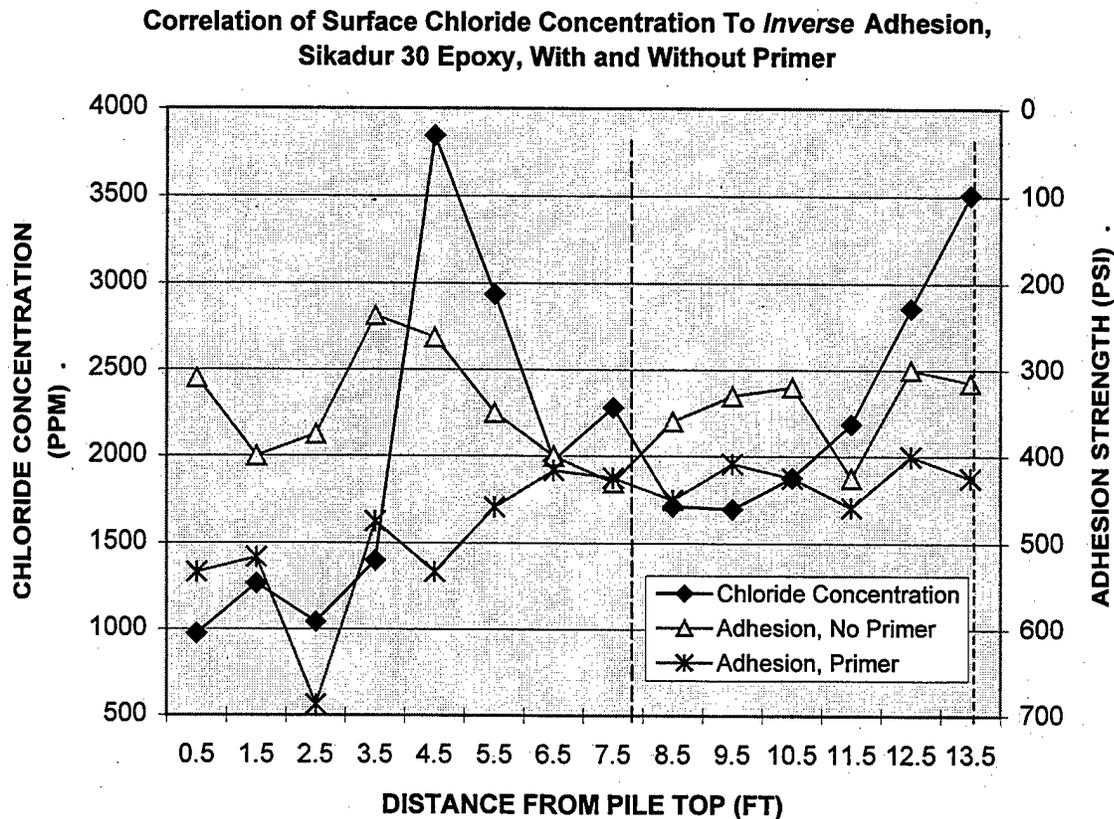


Figure 21. A Summary of the Data Relating the Surface Chloride Concentrations to the Inverse Adhesiveness of Sikadur 30 Epoxy to Pile #1, Face B, With and Without the Application of Sikadur 55 Primer

The plotted data of Figure 21 summarizes the data of Figures 17 and 19. The surface chloride concentrations correlate with the *inverse* of the adhesiveness of the Sikadur 30 epoxy with or without the Sikadur 55 primer.

6.7 The Correlation of the Surface Chloride Concentration of a Nonhydroblasted Surface to the Adhesiveness of Sikadur 30 Epoxy

Figure 22 shows how the chloride concentrations along the surface of Pile #1, Face D (a nonhydroblasted surface) relates to the adhesiveness of the Sikadur 30 epoxy.

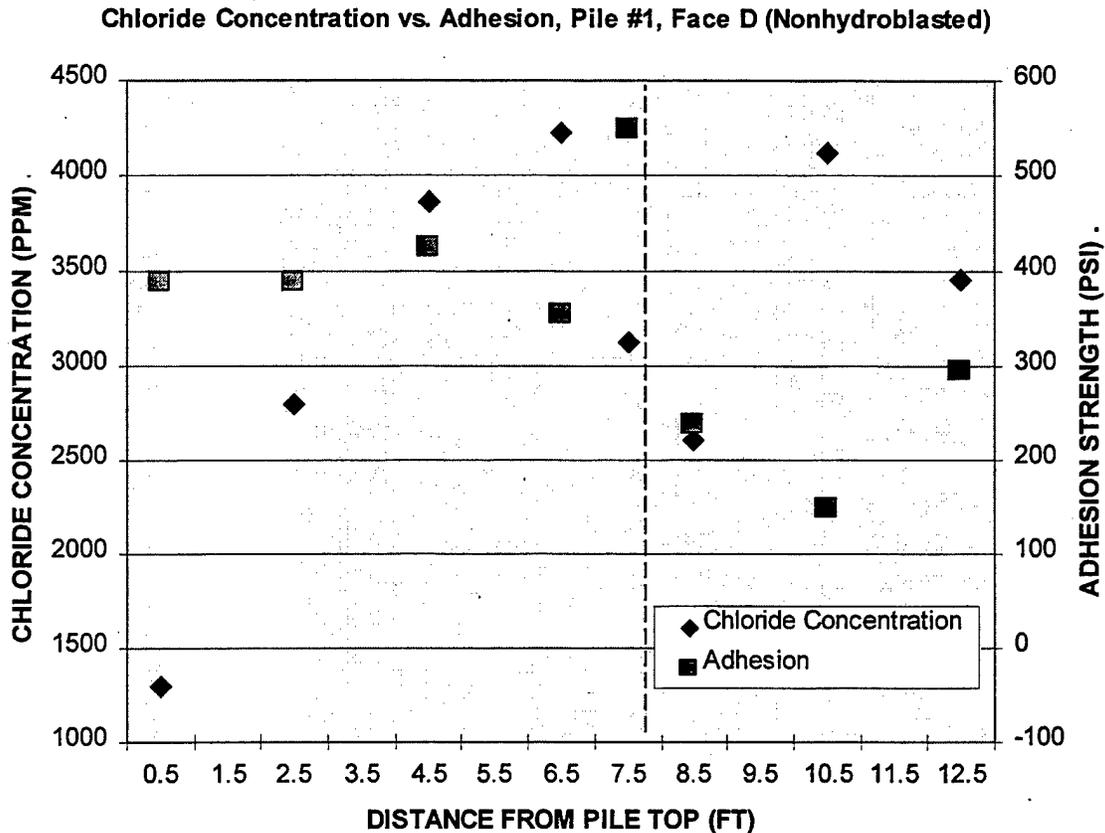


Figure 22. Chloride Concentrations along Pile #1, Face D (nonhydroblasted) vs. Adhesiveness of the Epoxy

The correlation of surface chloride concentrations to adhesiveness for the nonhydroblasted surface (Figure 22) is analogous to that for the hydroblasted surface (compare to Figure 16). Where the surface chloride levels are higher, the adhesiveness decreases, especially in the tidal zone and below. Above the tidal zone (top of the pile) the “pull-off” values appear to taper off and be less influenced by the chloride content; this is again borne out in Figure 23.

6.8 The *Inverse* Correlation of the Surface Chloride Concentration of a Nonhydroblasted Surface to the Adhesiveness of Sikadur 30 Epoxy

Figure 23 shows how the chloride concentrations along the surface of Pile#1, Face D (a nonhydroblasted surface) relates to *inverse* of the adhesiveness of the Sikadur 30 epoxy.

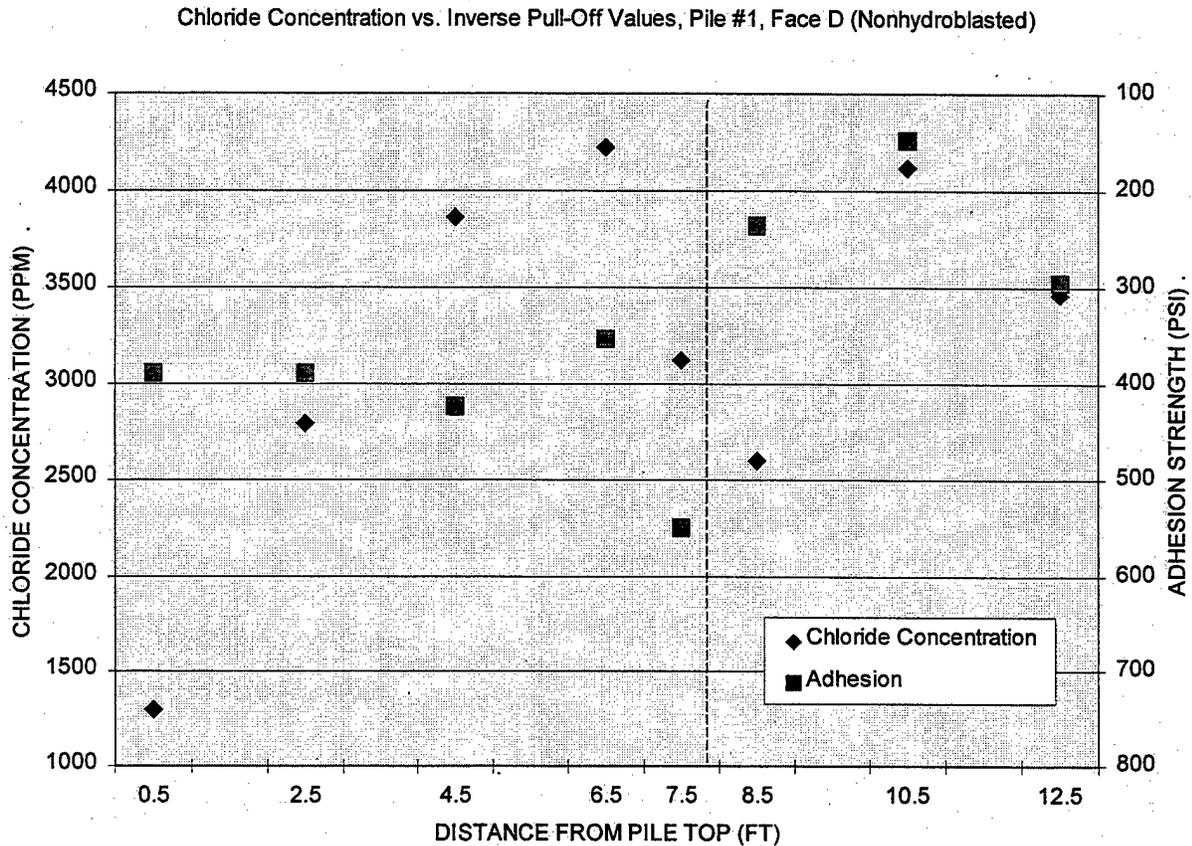


Figure 23. Chloride Concentrations along Pile #1, Face D (nonhydroblasted) vs. the Inverse Adhesiveness of the Epoxy

Figure 23 again (as in Figure 22) indicates a slight inverse correlation (mostly in the tidal zone and below) between adhesion and chloride concentration. This inverse correlation was also evident on the hydroblasted surface (compare to Figure 17).

7. EFFECT OF CHLORIDE ON THE ADHESIVENESS OF SIKADUR 32 EPOXY

Most data recorded and analyzed earlier in this report was based upon the adhesiveness of the Sikadur 30 epoxy. The Sikadur 32 epoxy is a less viscous adhesive and is generally not used for adhering carbon fiber strips, as was the focus of this study. However since the dollies had been applied, they were separated from the concrete surface using the elcometer.

7.1 The Correlation of Surface Chloride Concentrations of a Hydroblasted Surface to the Adhesiveness of Sikadur 32 Epoxy

Figure 24 shows the correlation of the surface chloride concentrations on Face B and the adhesiveness of the Sikadur 32 epoxy on Face A. Both of these surfaces are hydroblasted. The data should be viewed with some reservation in that Face B is a form surface and Face A is a top-of-the-form surface. The exposure to the marine environment of the two faces, however, should be the same.

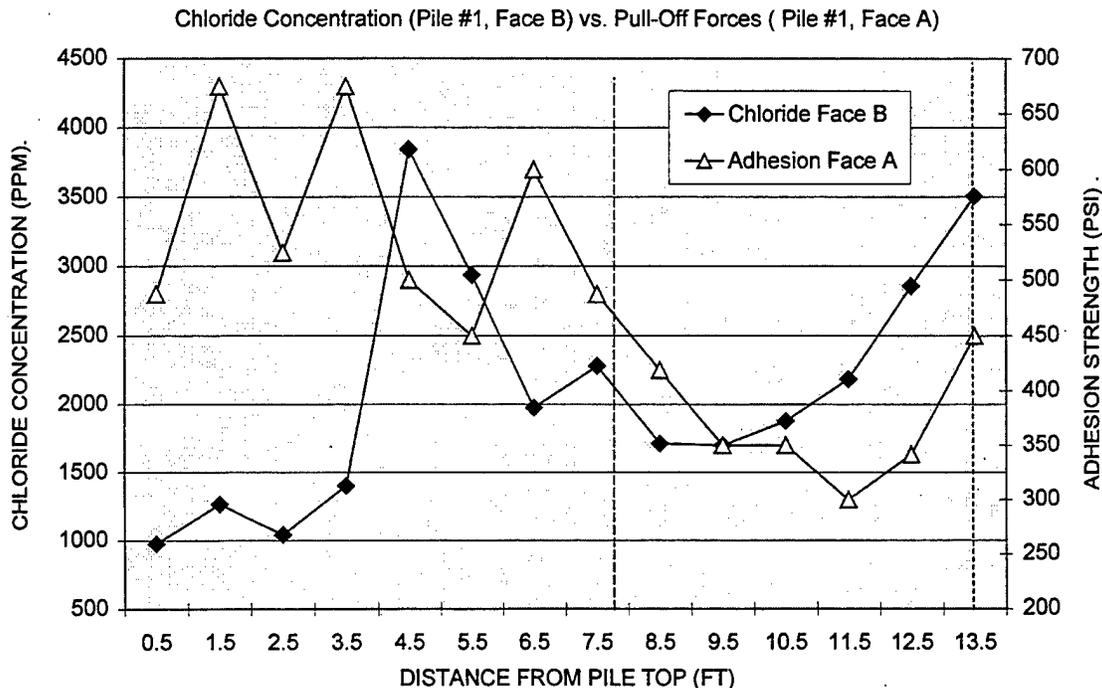


Figure 24. A Correlation of the Surface Chloride Concentrations (Face B) vs. the Adhesiveness of the Sikadur 32 Epoxy (Face A) Along Pile #1.

The plotted data of Figure 24 appears rather sporadic, although some correlation of chloride levels to adhesiveness of Sikadur 32 in the tidal zone and below is apparent. The plotted data of Figure 25 provides evidence of "some" correlation above the tidal zone.

7.2 The Inverse Correlation of Surface Chloride Concentrations of a Hydroblasted Surface to the Adhesiveness of Sikadur 32 Epoxy

Figure 25 shows the correlation of the surface chloride concentrations on Face B and the *inverse* adhesiveness (pull-off forces) of the Sikadur 32 epoxy on Face A.

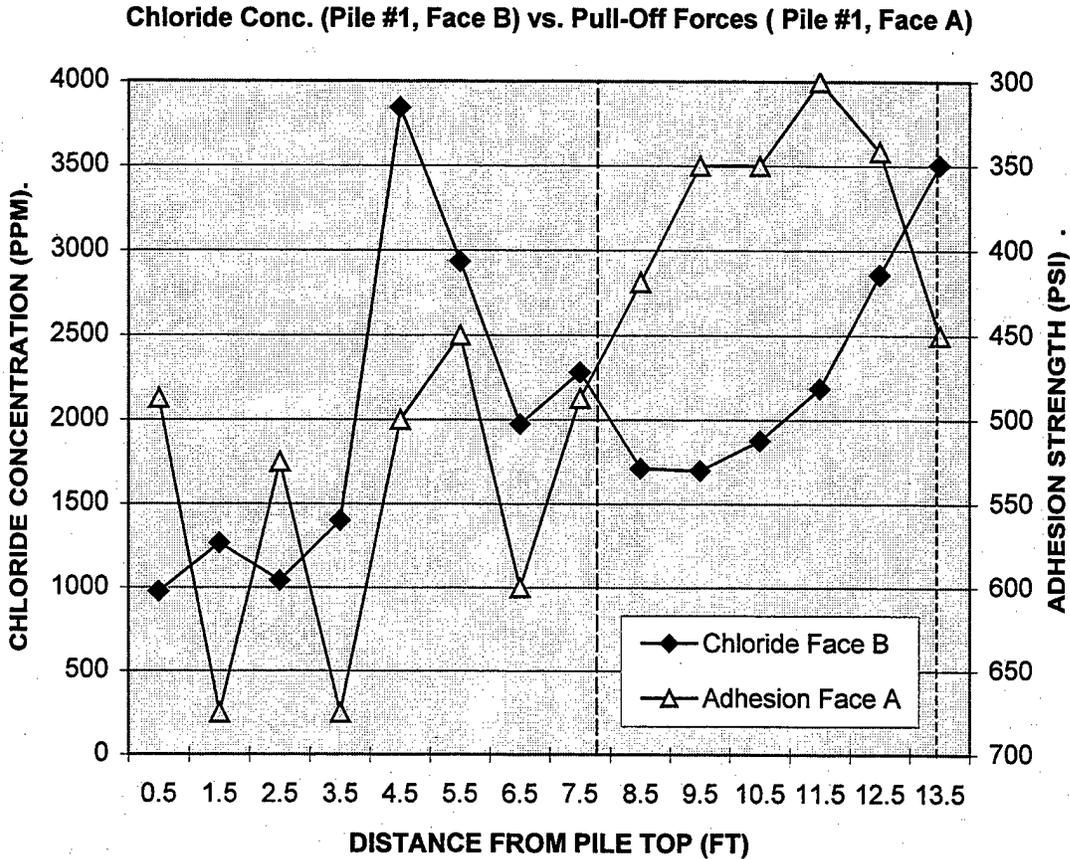


Figure 25. A Correlation of the Surface Chloride Concentrations (Face B) vs. the Inverse Adhesiveness of the Sikadur 32 Epoxy (Face A) Along Pile #1

The plotted data of Figure 25 again (as in the plotted data of Figure 17 and, questionably, Figure 23) indicates an inverse correlation of chloride levels to adhesiveness. This is especially apparent above the tidal zone: the higher the surface chloride concentration along the pile above the tidal zone, the lower is the adhesive strength of the epoxy.

8. EFFECT OF COMPRESSIVE STRENGTH OF HYDROBLASTED/ NON-FORM SURFACE

The surface of Pile #1, Face B was additionally analyzed using a rebound hammer [2], a test to determine the concrete compressive strength at the concrete surface.

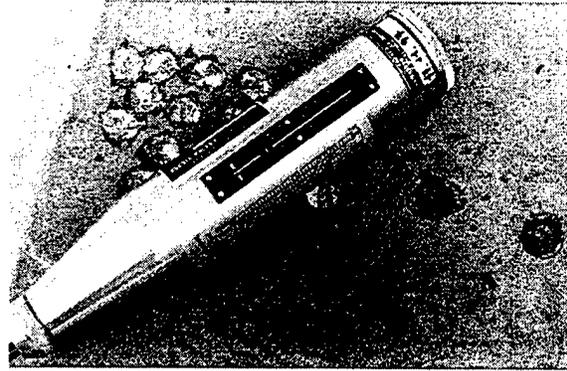


Figure 26. Rebound hammer.

8.1 Correlation of Chloride Concentrations to Compressive Strength

Figure 27 correlates the surface chloride concentrations to the compressive strength of the pile surface along the hydroblasted Face B.

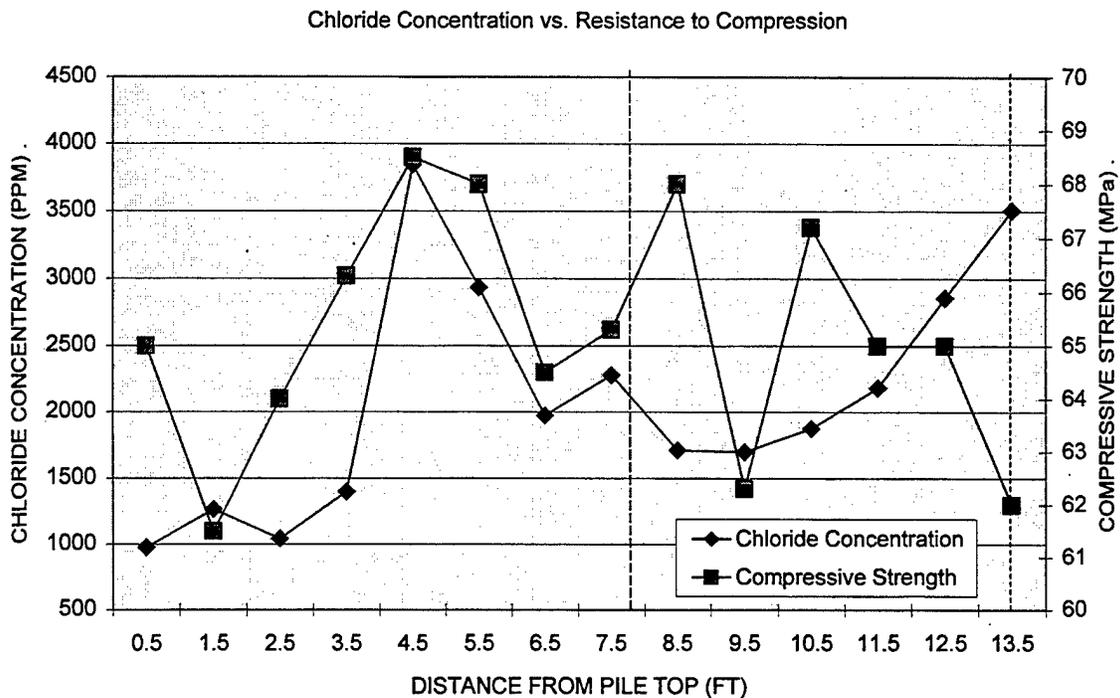


Figure 27. Correlation of Surface Chloride Concentrations and Compression Resistance Along Pile #1, Face B, a Hydroblasted Surface

The concrete compressive strength measured with a rebound hammer along the pile represents the density or compactness of the surface. Figure 27 indicates that, above the tidal zone, the concrete appears to be slightly denser where the surface chloride levels are high. Within the tidal zone and below, there appears to be little correlation.

8.2 The Inverse Correlation of the Adhesiveness of Sikadur 30 Epoxy to Concrete Compressive Strength at the Surface

Figure 28 compares the compressive strength to the adhesiveness of the Sikadur 30 epoxy along the pile surface.

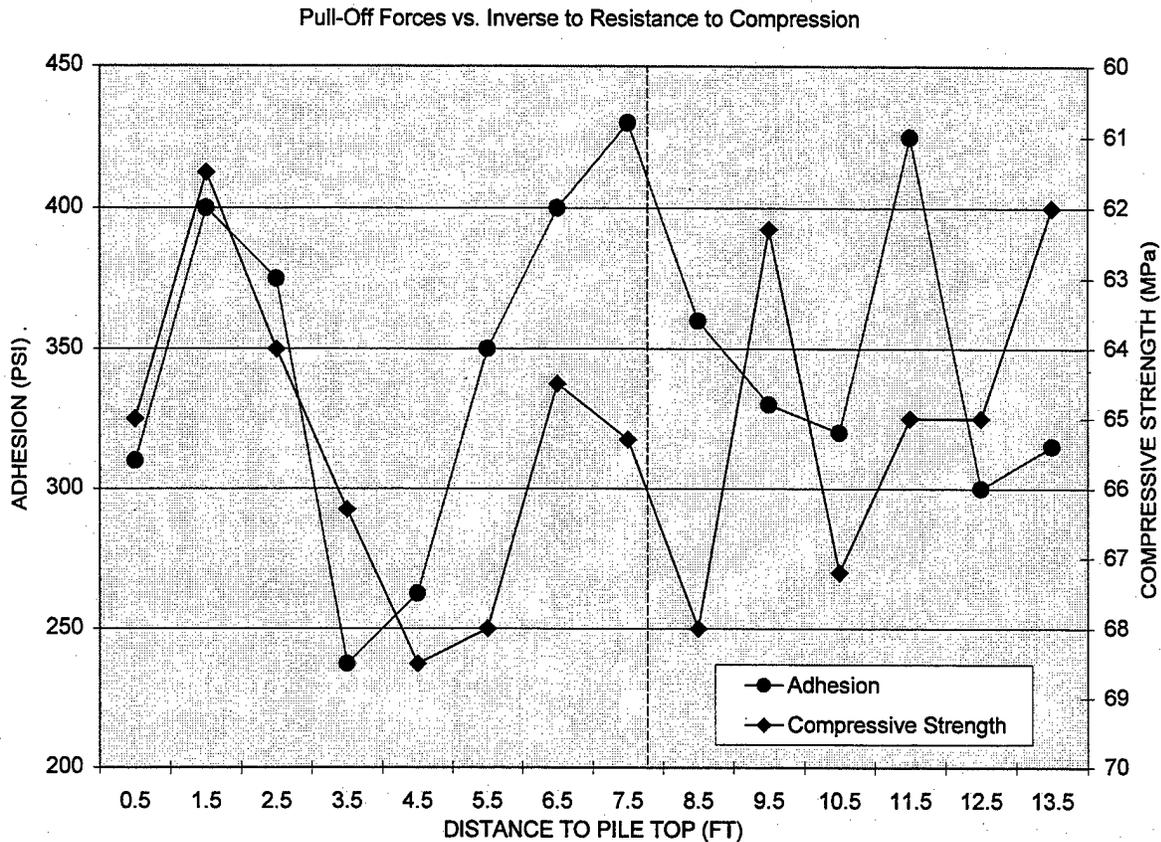


Figure 28. A Correlation of the Adhesiveness of Sikadur 30 Epoxy with the Compression Resistance of the Surface of Pile #1, Face B, a Hydroblasted Surface

The plotted data of Figure 28 is an inverse correlation of adhesiveness of the Sikadur 30 epoxy to the compression resistance of the concrete. This inverse correlation is apparent for the region of the pile above the tidal zone, a correlation that was also evident in Figure 27, that of the surface chloride concentrations. This inverse correlation is surprising but it may be actually due to the higher chloride content rather than the higher strengths, as shown in Figure 27.

9. CONCLUSIONS

The research for this project focused on the effect of surface chloride concentrations on the adhesion of two commercial epoxys, Sikadur 30 and 32, on a concrete pile that had been exposed to the marine environment for approximately 4 years. Additionally, various surface preparations of the pile were also considered: the surface parameters included hydroblasting (vs. nonhydroblasting) the surface, and the use of a primer coating (Sikadur 55) before the application of the epoxy.

The surface chloride concentrations were measured analytically with a chloride ion selective electrode. A general trend in the chloride levels along the pile was apparent (Figures 13 and 14).

The adhesive forces of the epoxy were measured with an elcometer. As might be expected the specific data points were rather erratic, but with the duplication of data points at selected locations along the pile, a general trend was also evident (Figures 7-11). A visual review of the dollies removed from the pile showed that separation occurred as a result of *total* concrete failure on about 50% of the dollies, located primarily in the region above the tidal zone. About 25% of the dollies showed mostly concrete failure (between 60% and 90% concrete failure), and about 25% showed mostly epoxy-concrete (adhesive) failure. No failure occurred within the relatively thick Sika CFRP strip.

Conclusive results for the effect of surface chloride concentrations on the adhesiveness of Sikadur 30 of a hydroblasted surface *without* the application of a primer indicate that as the surface chloride concentrations increase the adhesion of the epoxy decreases. This trend is especially true for the section of the concrete that is above the average tidal zone (Figure 17).

Hydroblasting by itself seems to provide some degree of improvement in the adhesion (Figure 9). Hydroblasting can remove a significant amount of chlorides (Figure 15), which in turn results in increased adhesion (Figure 17).

With the application of the primer, the trend appears to be similar, but less pronounced (Figure 18). This latter trend indicates that the surface chloride concentration may not be the major factor in this analysis, but rather the greater adhesiveness of the epoxy with the application of the primer on a more dense/compact concrete surface (Figures 27 and 28). One very evident factor in the adhesion of the epoxy is that the adhesive forces at all points along the pile were higher when the primer was applied (Figure 11). Hence both hydroblasting and the use of primer are recommended.

A correlation of the surface chloride concentrations on the adhesion of the Sikadur 30 epoxy on a nonhydroblasted surface is less conclusive. First, fewer data points were obtained. If any trend can be extracted from the data, an inverse correlation between the surface chloride concentrations and the adhesion of the epoxy is more apparent (compare Figures 22 and 23). This would be in agreement with the data interpretations from the hydroblasted surface. No "primer" data were obtained from the nonhydroblasted surface of the pile.

An additional factor that could affect adhesion was the compressive strength of the concrete, as measured at the surface using a rebound hammer. The surface chloride concentrations increased with the compressive strength of the concrete, especially above the tidal zone (Figure 27). However, where the surface compressive strength increased, the adhesive forces of the epoxy decreased (Figure 28). The latter observation may only indicate that the surface chloride concentrations, not the strength of the concrete at the surface, play the major role in affecting the adhesiveness of the epoxy. While a set of data for the surface chloride concentrations and the adhesion of the Sikadur 32 epoxy were obtained (Figures 24 and 25), any conclusions based upon that data should be carefully construed.

10. ACKNOWLEDGMENTS

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11. REFERENCES

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2. American Society for Testing and Materials, ASTM C-805, "Standard Test Method for Rebound Number of Hardened Concrete", Annual Book of ASTM Standards, 1997.